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METHODS AND SYSTEMS FOR CONTROLLING MOTION OF AND TRACKING A MECHANICALLY UNATTACHED PROBE

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Description

METHODS AND SYSTEMS FOR CONTROLLING MOTION OF AND TRACKING A MECHANICALLY UNATTACHED PROBE

Related Applications

This application claims the benefit of U.S. provisional patent application no. 60/449,930, filed February 25, 2003, the disclosure of which is incorporated herein by reference in its entirety.

Government Interest

This work was supported by NIH Grant Number 1R01EB000761-01. Thus, the U.S. Government has certain rights to this invention.

Technical Field

The present invention relates to methods and systems for controlling motion of and tracking a mechanically unattached probe. More particularly, the present invention relates to magnetic structures for magnetically controlling the motion of a mechanically unattached probe in one, two, or three dimensions, where the magnetic structures are compatible with high resolution optics used for imaging and tracking.

Background Art

In the field of scanning probe microscopy, small probes interact with samples under test to measure mechanical properties of the samples under test. For example, in atomic force microscopy, a small probe (typically sub-micrometer sized) is attached to the end of a cantilever. As the probe is scanned across the surface of a sample under test, such as the membrane of a cell, surface irregularities impose a varying force on the probe, which, in turn, results in a bending or deflection of the cantilever. An optical sensor senses the deflection of the cantilever based on light reflected from the cantilever and thereby determines changes in normal position of the probe as it is scanned across the surface of the sample under test. The changes in normal position of the probe are used to map the surface of the sample under test.

Figure 1A illustrates a typical application of atomic force microscopy. In Figure 1A, a probe **100** is attached to the end of cantilever **102** to map the surface **104** of a cell membrane. A laser, an optical sensor, and a computer (not shown) are used to map surface **104** as probe **100** causes deflections in cantilever **102**. One problem with atomic force microscopy is illustrated in Figure 1B. Atomic force microscopy requires a mechanical connection between probe **100** and the remainder of the system via cantilever **102**. As a result, conventional atomic force microscopy is unsuitable for measuring mechanical properties of structures within enclosed regions, such as organelles within a cell membrane, or the other structures that are inaccessible for scanning with a mechanically attached probe.

One way to measure properties of structures inside of cells and other enclosed environments is to mechanically decouple the probe from the remainder of the system. However, once the probe is mechanically decoupled from the remainder of the system, tracking and controlling movement of the probe become problematic. One known technique of applying force to a mechanically decoupled probe is referred to as "optical tweezers." This technique requires high optical field intensities that interact strongly with many materials and may produce undesirable side effects on experiments in biological samples.

Commonly-assigned, co-pending international patent application number PCT/US02/30853 describes a magnetic coil and pole assembly with four pencil-shaped pole pieces that converge from the vertices of an equilateral tetrahedron. Although such an assembly is useful in many environments, it may be desirable to control the motion of a probe in microscopes having high numerical aperture (NA) objective lenses with short focal distances. For example, some lenses may have numerical apertures greater than or equal to one at focal distances on the order of millimeters. Such lenses typically have large diameters and thus limit the space for placement of magnetic pole pieces used to control the motion of mechanically unattached probes. The space for placing pole pieces is even further limited when high NA objective lenses are placed both above and below the sample under test. In addition, at some positions within the volume defined by the pole pieces in a four-pole system, moving the probe in certain directions can be difficult.

Another factor to be considered in designing and placing magnetic pole pieces to control motion of a mechanically unattached magnetic probe is that the magnetic force on the probe for a given magnetic field varies inversely with r^5, where r is the distance from the pole tip applying the magnetic force to the magnetic probe. Thus, in order to apply strong magnetic forces to a probe, it is desirable that the pole tips be kept as close as possible to the probe. However, because the pole tips compete for space with imaging and tracking optics, designing a system that achieves desired magnetic forces and that is compatible with high-resolution optics is difficult.

Accordingly, there exists a long felt need for improved magnetic structures for applying magnetic force to a mechanically unattached probe that are suitable for use with high resolution optics or in other space-constrained environments.

Disclosure of the Invention

The present invention includes methods and systems for controlling and tracking the motion of a mechanically unattached probe. By mechanically unattached, it is meant that the probe is not mechanically attached to its motion control system. The present invention is not limited to controlling the motion of a probe that is not mechanically attached to anything. For example, a probe may be weakly bound to a surface of a sample under test and be allowed to diffuse on the surface. In another example, a probe may be bound to the surface of a sample under test and forces may be applied to the probe in a direction normal to the surface to measure the forces that bind the probe.

According to one aspect of the invention, a magnetic coil and pole assembly for controlling motion of a mechanically unattached probe is provided. The assembly includes at least one magnetic pole carrier. The pole carrier includes a light transmissive substrate and a plurality of magnetic pole pieces being patterned on the substrate in a manner for applying force to a mechanically unattached magnetic probe. A magnetic drive core is magnetically coupled to the magnetic poles to provide a low reluctance return path for the magnetic flux induced between the poles. A plurality of magnetic coils is wound around the drive core for conducting current and applying magnetic force to the probe.

In one implementation, the magnetic pole carrier comprises a slide cover slip and the magnetic poles are thin film structures patterned on the cover slip. Using a slide cover slip is advantageous because it is thin and light transmissive. Using thin film magnetic poles is also advantageous due to the thinness of the poles and the ability to fabricate the poles using semiconductor manufacturing processes. However, the present invention is not limited to using a slide cover slip for the pole plate or using thin film magnetic poles. Any light transmissive substrate and pole structure suitable for use with high numeral aperture lenses in an optical microscope are intended to be within the scope of the invention. For example, in an alternate implementation, the pole pieces may be laminated foil structures cut from a sheet of magnetic material rather than thin film structures manufactured using semiconductor manufacturing techniques.

If three dimensional motion control is desired, a hexapole pole piece arrangement may be used for the magnetic coil and pole assembly. In alternate arrangements, thin film magnetic poles may be formed in arbitrary patterns on a substrate to apply desired magnetic forces to one or more mechanically unattached magnetic probes in one, two, or three dimensions. For example, if motion in a single direction is desired, a magnetic pole and coil assembly of the present invention may include a single thin film or thin foil pole piece located on a light transmissive substrate. Locating any number of pole pieces on a light transmissive substrate is intended to be within the scope of the invention.

Accordingly, it is an object of the invention to provide magnetic structures for controlling motion of a mechanically unattached magnetic probe.

It is another object of the invention to provide a magnetic coil and pole assembly for controlling motion of a mechanically unattached magnetic probe and that is suitable for use with high numerical aperture lenses.

Some of the objects of the invention having been stated hereinabove, and which are addressed in whole or in part by the present invention, other objects will become evident as the description proceeds when taken in connection with the accompanying drawings as best described hereinbelow.

Brief Description of the Drawings

Preferred embodiments of the invention will now be explained with reference to the accompanying drawings of which:

Figures 1A and 1B are sectional views of a biological cell and a probe associated with conventional atomic force microscopy techniques;

Figure 2 is a block diagram of a three-dimensional force microscope instrument including a magnetic coil and pole assembly according to an embodiment of the present invention;

Figures 3A and 3B are schematic diagrams illustrating exemplary lenses having different numerical apertures;

Figure 4A is a perspective view of a cube illustrating exemplary pole placements for a hexapole design according to an embodiment of the present invention;

Figure 4B is a plan view of triangles **402** and **404** viewed along line **406** illustrated in Figure 4A;

Figure 4C is a perspective view of a hexapole arrangement for magnetic pole pieces according to an embodiment of the present invention;

Figure 5A is a perspective view of a magnetic pole and coil assembly according to an embodiment of the present invention;

Figure 5B is a side view of a pole piece, upper and lower pole carriers, and portions of upper and lower drive ring cores according to an embodiment of the present invention;

Figure 6 is a perspective view of a magnetic drive ring core according to an embodiment of the present invention;

Figure 7 is a top view of a magnetic drive ring core with magnetic coils being wound around the core according to an embodiment of the present invention;

Figure 8 is a top view of a lower pole carrier patterned with thin film magnetic pole pieces according to an embodiment of the present invention;

Figure 9 is a top view of a lower pole carrier and a lower magnetic drive ring core according to an embodiment of the present invention;

Figure 10 is a top view of an upper magnetic drive ring core and upper pole carrier according to an embodiment of the present invention;

Figure 11 is a top view of upper and lower magnetic cores and upper and lower magnetic pole carriers according to an embodiment of the present invention;

Figure 12 is a side view of a magnetic coil and pole assembly and upper and lower objective lenses according to an embodiment of the present invention;

Figure 13 is a top view illustrating exemplary magnetic forces that may be used to pull a probe towards one pole piece in a hexapole arrangement according to an embodiment of the present invention;

Figure 14A is a top view of a pole carrier including peaked magnetic pole pieces according to an embodiment of the present invention;

Figure 14B is a close-up view of the pole carrier with peaked magnetic pole pieces illustrated in Figure 14A;

Figure 15A is an optical schematic diagram illustrating exemplary imaging optics suitable for imaging a mechanically unattached magnetic probe according to an embodiment of the present invention;

Figure 15B is a top view illustrating magnetic pole pieces as viewed through an objective lens;

Figure 16 is an optical schematic diagram illustrating exemplary tracking optics suitable for tracking motion of a mechanically unattached magnetic probe according to an embodiment of the present invention;

Figure 17 is a perspective view illustrating exemplary coordinates and angles used in equations for tracking a mechanically unattached magnetic probe in three-dimensions according to an embodiment of the present invention;

Figure 18A is a graph of a linear profile of a normalized Z displacement signal generated by a system for tracking a mechanically unattached magnetic probe in three dimensions according to an embodiment of the present invention; and

Figure 18B is a graph of a linear profile of a normalized X displacement signal generated by a system for tracking a mechanically unattached magnetic probe in three dimensions according to an embodiment of the present invention.

Detailed Description of the Invention

The methods and systems for controlling motion of and tracking a mechanically unattached magnetic probe may be implemented in 3D force microscopes with high numerical aperture lenses. Figure 2 is a block diagram of an exemplary 3D force microscope in which a magnetic coil and pole assembly of the present invention may be used. Referring to Figure 2, the system includes magnetic coil and pole assembly **200** for controlling the force applied to a mechanically unattached magnetic probe **202**. The magnetic force

supplied by assembly **200** is controlled by a computer **204**. More particularly, D/A board **210** converts the digital coil control signal output from computer **204** into analog format. Power amplifiers **212** amplify the signal voltages output from D/A board **210** and output the amplified signals to magnetic coil and pole assembly **200** as pole magnetizing currents. Magnetic coil and pole assembly **200** transduces the pole magnetizing currents to magnetomotive forces which induce a magnetic field that is coupled to probe **202**, thereby generating a magnetic force on probe **202**.

The system also includes a piezoelectric (x, y, z) translation stage **206** controlling position of sample under test (SUT) **205**, which physically contains probe **202**. The motion of SUT **205** is coupled to probe **202** by the viscoelastic properties of SUT **205**, thereby also affecting the motion of probe **202**. A position control feedback loop comprises position gauge **230**, PID controller **232**, and high voltage driver **234** in controller module **208**; and piezoelectric actuators **226** and capacitive position sensors **228** in translation stage **206**. This feedback loop is used to rapidly and accurately cause the position of SUT **205** to follow a position control signal from computer **204**, and to feed back a stage position signal to computer **204** representing the measured position of SUT **205**.

In order to image and track probe **202**, the system illustrated in Figure 2 includes various optical components. These components may include laser **214**, optics **216**, and optics **218**. Laser **214** generates light to be scattered from probe **202** and used to track probe **202**. Optics **216** includes a series of lenses

used for both tracking and imaging. Optics **218** collect light scattered by probe **202**, light scattered by the sample being monitored, and light transmitted directly from laser **214**. A quadrant photodiode **220** (QPD) converts the light collected by optics **218** into electronic signals used to determine the position of probe **202**. Transimpedance amplifiers **222** convert the currents output by QPD **220** into voltages indicative of probe position. An A/D board **224** converts the voltages output from transimpedance amplifiers **222** into digital signals indicative of probe position. Computer **204** executes codes, which transform the probe position signals from A/D board **224** into estimates of the (x, y, z) position of probe **202** relative to the center of the beam waist of laser **214** at the focus of optics **216**. The functional range of this method is limited to a radius of approximately one wavelength of the light of laser **214** from the center of the beam waist.

Maintaining the probe within this functional range is essential to the operation of the system. This is accomplished using feedback methods in various operational modes. In all modes, the feedback minimizes the estimated (x, y, z) position of probe **202** relative to the center of the beam waist of laser **214** at the focus of optics **216**.

One mode in which the system illustrated in Figure 2 may be operated is position control mode. In position control mode, computer **204** provides a desired position control signal to cause the position of SUT **205** to follow a predetermined trajectory. Computer **204** also executes feedback code driving the force control signal to cause probe **202** to remain fixed relative to the beam waist. This is equivalent to causing probe **202** to move relative to SUT **205** in a

trajectory that is exactly opposite the predetermined trajectory of SUT **205**. The force control signal represents the forces applied to probe **202** to cause it to follow this trajectory. This mode is useful for measuring viscoelastic properties such as fluid viscosity in SUT **205**.

Another mode is force control mode. In force control mode, computer **204** provides a desired force control signal to apply a predetermined force profile to probe **202** over time. Computer **204** also executes feedback code driving the position control signal to cause probe **202** to remain fixed relative to the beam waist. This is equivalent to causing probe **202** to move relative to SUT **205** in a trajectory that is exactly opposite the motion caused by the position control signal. The position control signal represents the trajectory followed by probe **202** in response to the applied force signal.

A mode closely related to position control mode is velocity control mode. In velocity control mode, Computer **204** calculates a position trajectory satisfying initial conditions and a predetermined desired velocity profile, and uses position control mode to cause probe **202** to follow this position trajectory.

The present invention is not limited to these operational modes. Any combination of feedback from stage position and probe position signals to force control and position control signals is intended to be within the scope of the invention. In addition, the present invention is not limited to using the forward light scattering method described with respect to Figure 2 to measure probe position. In an alternate implementation, video imaging may be used to track the position of probe **202** without departing from the scope of the invention. Using video imaging may provide further operational modes.

High NA Lenses

As stated above, the present invention preferably includes magnetic structures that are suitable for use with high numerical aperture objective lenses. Figures 3A and 3B illustrate lenses with different numerical apertures. In Figure 3A, a lens **300** is spaced from a sample under test **302** by the focal distance of lens **300**. The angle α, which is one half of the angle from the sample to the outside edges of lens **300**, determines the numerical aperture. Assuming that the medium between lens **300** and sample **302** has an optical index of refraction η, the numerical aperture is equal to $\eta\sin(\alpha)$. In Figure 3B, another lens **304** has a larger diameter and shorter focal length than lens **300**. As a result, the angle α and hence the numerical aperture of lens **304** is larger than that of lens **300**. As the diameter of a lens increases and the focal length decreases, the numerical aperture approaches one. For lenses with a numerical aperture of one or greater, the space for placing magnetic pole pieces is limited. Accordingly, the present invention preferably includes pole piece structures that are capable of controlling motion of a magnetic probe near high numerical aperture lenses or in other space-constrained environments.

Hexapole Geometry for Magnetic Coil and Pole Assembly

In some applications, it may be desirable to control the motion of a mechanically unattached probe in any direction in three dimensions. One design for magnetic coil and pole assembly **200** that is suitable for three dimensional motion control is a hexapole design. In the hexapole design, six thin film or laminated foil poles are used to control the motion of a mechanically

unattached probe in three dimensions. Figure 4A illustrates the concept behind pole placement for the hexapole design. In Figure 4A, if a sample under test is placed at the center of a cube **400**, the sample is equidistant from the midpoints of each face of cube **400**. In addition, the lines that connect the midpoints of opposite faces of cube **400** are orthogonal to each other. These lines form a Cartesian coordinate system. Thus, the midpoints of the faces are ideal locations for placement of the magnetic pole tips.

If the midpoints of adjacent faces of cube **400** are connected as shown in Figure 4A, two equilateral triangles **402** and **404** are formed. The equilateral triangles are parallel to each other and are rotated with respect to each other by 60°. Figure 4B illustrates triangles **402** and **404** looking along dashed line **406** shown in Figure 4A. In Figure 4B, it can be seen that the vertices of triangles **402** and **404** are equidistant from the center of cube **400** in Figure 4A. In addition, triangles **402** and **404** define a cylindrical working volume **408** between them. This working volume represents the area in which motion of probe **202** can be controlled in three dimensions. However, the present invention is not limited to controlling the motion of probe **202** in cylindrical working volume **408**. For instance, it may be desirable to apply increased force on the probe at the expense of force symmetry. In such an instance, the sample may be placed near one of the pole tips for increased magnetic force.

Figure 4C illustrates the result of placing thin film or laminated foil magnetic pole pieces with pole tips located at the vertices of triangles **402** and **404** illustrated in Figures 4A and 4B. In Figure 4C, pole pieces **410** lie in a common plane with pole tips corresponding to vertices of triangle **402**.

Similarly, pole pieces **412** lie in a common plane with pole tips corresponding to vertices of triangle **404**. Pole pieces **410** are rotated by an angle of 60° with regard to pole pieces **412**. Like the planes that contain triangles **402** and **404**, the plane that contains pole pieces **410** is parallel to the plane that contains pole pieces **412**.

In one exemplary implementation, the hexapole design may be implemented by providing pole pieces **410** and **412** on upper and lower carriers and providing pairs of magnetizing coils for magnetizing each pole piece. Figure 5A is a perspective view of magnetic pole and coil assembly **200** where the assembly includes a hexapole geometry as illustrated in Figure 4C. Referring to Figure 5A, assembly **200** includes an upper pole carrier **500** and a lower pole carrier **502**. Upper pole carrier **500** includes pole pieces **410** located on an upper surface thereof. Lower pole carrier **502** includes pole pieces **412** located on a lower surface thereof.

In order to apply magnetic force to a mechanically unattached probe, assembly **200** includes upper and lower magnetic coil assemblies **504** and **506**. Assemblies **504** and **506** each include a plurality of magnetic coils **508** being wound around tabs **510** on upper and lower magnetic drive ring cores **512A** and **512B**. Assembly **200** may also include a mounting stage **514** for holding the cores, coils, carriers, and the sample. In the illustrated example, mounting stage **514** includes a hinged portion **516** for holding upper magnetic coil assembly **504**. In operation, hinged portion **516** is closed to bring assembly **504** in close proximity to the pole pieces located on upper pole carrier **502**.

The surface of each tab **510** that faces one of the pole pieces **410** or **412** is referred to as a pole face. When hinged portion **516** is closed, there may be air gaps between the pole faces and the pole piece that each pole face pair is magnetizing. Figure 5B illustrates this concept. Referring to Figure 5B, coils **508** and associated tabs **510** are located on opposite sides of pole piece **410**. The distance between the lower face of upper tab **510** and pole piece **410** is illustrated as h_1. The distance between lower tab **510** and pole piece **410** is illustrated by h_2. In order to ensure a low reluctance path for flux emanating from tabs **510** to pole piece **410**, it is preferable that the distances h_1 and h_2 be much less than the cross sectional area formed by the intersection of the pole faces formed by tabs **510** and pole piece **410**. For example, the cross sectional area formed by the intersection of the pole face and pole piece **410** is preferably at least one order of magnitude and even more preferably at least two orders of magnitude greater than h_1 and h_2. Providing a large cross sectional area relative to h_1 and h_2 compensates for the increase in reluctance caused by the air gap and glass material between the pole faces and pole piece **410**.

Figure 6 is a perspective view of magnetic drive ring core **512A** or **512B** according to an embodiment of the present invention. Magnetic drive ring core **512A** is preferably identical in structure to magnetic drive ring core **512B**. Referring to Figure 6, magnetic drive ring core **512A** or **512B** includes tabs **510** around which coils **508** may be wound. Drive ring core **510** is preferably made of a material with resistance to eddy currents, hysteresis, and magnetostriction, yet with high permeability. Such characteristics allow a large flux to be

generated, while minimizing losses due to eddy currents. One material suitable for forming drive ring core **512A** or **512B** is tape wound laminated metglass. Tabs **510** are preferably equally spaced around core **512A** or **512B**.

Figure 7 is a top view illustrating coils **508** wound around tabs **510** of core **512A** or **512B**. In Figure 7, each coil is formed of a single layer spiral of flat magnetic wire. Coils **508** form an aperture **700** suitable for placement of high resolution optics. For the hexapole geometry, there are preferably six coils on each drive ring--an upper coil and a lower coil for each pole piece.

Figure 8 is a top view of lower pole carrier **502** including lower pole pieces **412**. In Figure 8, lower pole pieces **412** are on the underside of pole carrier **502**. In one exemplary implementation, magnetic thin films may be photolithographically patterned on glass substrates and then electroplated with permalloy to form pole plates. That is, pole pieces **410** and **412** may be patterned on glass carriers **500** and **502** to form upper and lower pole plates. In an alternate manufacturing method, pole pieces **410** and **412** may be patterned on glass carriers **500** and **502** by cutting the appropriate shapes from thin sheets of permalloy foil and then laminating the pole pieces onto carriers **500** and **502**. Each pole plate may include three poles in the hexapole arrangement. As illustrated in Figure 5A, the two pole plates make up the six poles of the hexapole geometry. The upper and lower pole carriers may be identically patterned. However, since one pole plate is flipped relative to the other pole plate, it is oriented with a rotation of 60° with respect to the other pole plate.

The present invention is not limited to using glass for pole carriers **500** and **502**. Any material that is transmissive to electromagnetic energy at the wavelengths used for imaging and/or tracking is intended to be within the scope of the invention. The present invention is likewise not limited to using permalloy for pole pieces **410** and **412**. Any suitable magnetic material with low hysteresis, low eddy currents, high saturation flux, and high permeability may be used without departing from the scope of the invention.

The thicknesses of pole pieces **410** and **412** may be selected based on a variety of engineering trade-offs. For example, in a configuration in which pole pieces **410** and **412** are sandwiched between upper and lower high NA objective lenses, the focal distances of the lenses, the space required for the sample slide, and the space required for pole carriers **500** and **502** limit the thicknesses of pole pieces **410** and **412**. Pole pieces **410** and **412** are preferably made thick enough so that they do not saturate with magnetic flux before the flux reaches the pole tips. In a high force application where increased magnetic force is more important than three dimensional motion control symmetry, pole pieces **410** and **412** can be made thicker and located in the same plane.

Figure 9 is a top view of lower pole carrier **502** mounted on lower drive ring core **512B**. For simplicity of illustration, coils **508** are not shown. In Figure 9, each pole piece **412** is patterned on the surface of pole carrier **502** that faces the pole faces of tabs **510**. The remaining tabs of lower drive ring core **512B** are used to magnetize pole pieces **410** of upper pole carrier **500** (not shown in Figure 9).

Figure 10 is a top view of upper magnetic drive ring core **512A**. In Figure 10, tabs **510** are located on the lower surface of core **512A**. Pole pieces **412** are patterned on the surface of pole carrier **500** that faces the corresponding pole faces of tabs **510**. The remaining tabs **510** are used to magnetize coils **412** on lower pole carrier **502**. In the configuration illustrated in Figure 11, each pole piece **410** and **412** is sandwiched between two tabs **510** to provide a low reluctance path for magnetic flux.

Figure 11 is a top view of upper and lower magnetic pole carriers **500** and **502** and upper and lower drive ring cores **512A** and **512B** in a sandwiched configuration. It can be seen from Figure 11 that when pole carrier **500** is placed on top of pole carrier **502**, pole pieces **410** and **412** form the hexapole geometry. Although not illustrated in Figure 11, a specimen slide may be placed between upper and lower pole carriers **500** and **502**. The specimen slide may include a mechanically unattached probe located in an aqueous medium so that magnetic force can be applied on the probe using pole pieces **410** and **412**.

Figure 12 is a side view of magnetic coil and pole assembly located in a space-constrained environment with high NA lenses on opposite sides of the assembly according to an embodiment of the present invention. Referring to Figure 12, upper and lower pole carriers **500** and **502** are located on opposite sides of sample plate **518**. It can be seen that due to the compact configuration of the upper and lower pole carriers, a lens **1200**, which may be a high numerical aperture lens (NA ≥ 1), may be placed in close proximity to the sample. Another lens **1202**, which may also be a high NA lens, may be placed

above assembly **200**. In an alternate configuration, either lens may be replaced by a lower NA lens (NA < 1) without departing from the scope of the invention. The gaps between lenses **1200** and **1202** and the respective pole carriers may be filled with a predetermined material to increase the numerical aperture of the lenses. In one example, the predetermined material may be water. The sample under test may be imaged through lower pole carrier **502**. The tracking laser may also pass through lower objective lens **1200**, lower pole plate **502**, upper pole plate **500**, and into lens **1202**.

In order to drive one of the pole pieces **410** or **412**, it is desirable to magnetize the upper and lower coils **508** above and below the pole piece being magnetized so that each coil has the same magnetic sense in the direction of the pole piece. That is, the upper and lower coils for a particular pole piece are preferably magnetized so that the north poles or the south poles of the coils face each other. This may be accomplished by wiring coils in the same vertical stack in series and winding the coils in opposite directions so that a current flowing in a given direction in each coil pair results in either the north or south poles facing each other.

Magnetizing the coils so that like poles face each other directs magnetic flux in the direction of the pole tip of the pole piece and into the sample. The flux may return through the other pole tips and the drive ring cores. It should be noted that it is not desirable to magnetize coils in the same vertical stack so that unlike poles face each other. For example, if a north pole in a vertical coil stack faces a south pole, flux emanating from the north pole will terminate in

the south pole, rather than flowing through the pole piece. This is undesirable since less flux will reach the magnetic probe.

In order to effect motion towards one of the pole pieces, the pole piece may be energized with a magnetic force that is stronger in magnitude than the magnetic force of the other pole pieces. In addition, the magnetic sense of the pole piece towards which motion is desired is preferably opposite that of the other pole pieces. Figure 13 illustrates this concept. Referring to Figure 13, one pole piece **412** is preferably magnetized with a magnetizing force of 5N, indicating a strong magnetic force with a north magnetic sense. The remaining pole pieces are preferably magnetized with weak south fields S, where S represents a field that is equal in magnitude to N. Probe **202** will travel in the direction of increasing magnetic flux. In Figure 13, the probe will travel in the direction of the 5N pole piece. By utilizing different magnetizing currents and the geometry illustrated in Figure 5A, motion of probe **202** in three dimensions can be achieved.

Alternate Pole Piece Geometries

Although the examples described above with regard to Figures 4A through 13 illustrate a hexapole design, the present invention is not limited to using a hexapole design. Forming any thin film or thin foil pole piece structure on a pole carrier to achieve a desired magnetic force on one or more mechanically unattached probes is intended to be within the scope of the invention. Figure 14A is a top view of a pole carrier **1400** with an alternate pole piece configuration. Figure 14B is a close-up view of the pole pieces and

pole carrier illustrated in Figure 14A. In Figures 14A and 14B, pole carrier **1400** may be a glass substrate, as described above. In Figure 14, pole carrier **1400** includes pole pieces **1402** and **1404**. Pole pieces **1402** and **1404** may be thin films or thin foils formed in a peaked or sawtooth pattern to form a plurality of opposing pole tips **1406** for applying forces over a wide area of a sample. Pole pieces **1402** and **1404** may be coupled to coil and pole assembly **200** at locations indicated by dotted lines in Figure 14A. Pole tips **1406** may be magnetized in any suitable manner to apply force to a plurality of mechanically unattached probes. For example, pole tips **1406** on pole piece **1402** may be initially magnetized to have a north magnetic sense and pole tips **1406** on pole piece **1404** may be initially magnetized to have a south magnetic sense. A plurality of magnetic probes may be placed between the pole tips in the sample under test. The magnetic polarity of the pole tips may be alternated over time and the force response of the sample under test may be measured over a period of time.

Imaging Optics

As discussed above, the present invention may include imaging optics for viewing probe **202** in the sample under test. Figure 15A is an optical schematic diagram of exemplary imaging optics suitable for use with the methods and systems of the present invention. Referring to Figure 15A, the imaging optics include a light source **1500** for illuminating the object being imaged. Light source **1500** may be any suitable light source capable of uniform illumination of an object. In a preferred embodiment, light source **1500** is a

fiber light consisting of a halogen lamp and a bundle of optical fibers with the output coupled to the lower end of the imaging optics. An exemplary commercially available light source suitable for use with the present invention is the M1000 Fiber Light available from Edmond Optics.

In a preferred embodiment of the invention, Koehler illumination is used to illuminate the subject. In Koehler illumination, light from the light source is focused by a collector lens to form an image of the light source on the back focal plane of a condenser. Accordingly, in Figure 15A, collector lenses **1502** form an image of light source **1500** on the back focal plane of a condenser **1200**. Condenser **1200** is an objective lens that corrects for spherical aberration, coma, and chromatic aberration and is optimized for bright field illumination. Probe **202** being imaged is located at the focal point of condenser **1200** in a sample chamber **1504**. Upper objective lens **1202** forms an image. A tube lens **1506** focuses the lights rays exiting objective **1202** onto the image plane of a CCD camera **1510**. A filter **1508** filters the light entering CCD camera **1512**. CCD camera **1510** converts the incident photons into an electronic signal and produces an electronic image of probe **202** and the sample under test.

The imaging system illustrated in Figure 15A is referred to as a bright field imaging system. However, the present invention is not limited to using bright field imaging. For example, in an alternate embodiment of the invention, fluorescent imaging can be used to produce electronic images of probe **202** and the sample under test.

One problem with any magnetic pole and core assembly in which the pole pieces intrude in the optical path is that the pole pieces may adversely affect imaging and tracking because the pole pieces block light rays that would otherwise be collected by the objective lenses. Figure 15B illustrates this concept. Figure 15B is a schematic diagram illustrating an exemplary view of the system as seen through upper objective lens **1202**. In Figure 15B, upper pole pieces **410** appear as fuzzy opaque regions in the scene because they are out of focus. Lower pole pieces **412** also appear as out of focus images, since they are outside the focal length of objective lens **1202**. In order to compensate for the effect of pole pieces **410** and **412** on imaging and tracking, the optical signal exiting lenses **1200** and **1202** can be post processed using a filter function to account for any distortion caused by the pole pieces. The filter function may be the inverse of the transfer function caused by the interference of pole pieces **410** and **412** on incident light. Such a transfer function may be experimentally determined and programmed into computer **204** illustrated in Figure 2.

Tracking Optics

In order to control the position of a mechanically unattached probe in three dimensions, it is necessary to be able to track the probe in three dimensions. Additional reasons for and advantages of tracking the probe in three dimensions are that such tracking allows mapping of surfaces within a tracked volume, and when coupled with applied force measurements, viscoelastic properties of samples under test can be determined. For example,

three-dimensional optical tracking while applying forces in three dimensions can be used to determine mechanical properties of structures within a cell, within a cell culture, or in any other biological sample. Selective binding of the probe to specific organelles and large macromolecules can be used to determine binding coefficients.

Figure 16 illustrates exemplary tracking optics that may be used in a system for three dimensional tracking and position control of a free floating probe according to an embodiment of the present invention. In Figure 16, the tracking optics include a laser light source **214** coupled to the remainder of the optics via a single mode optical fiber **1600**. A collimating lens **1602** collimates the diverging light rays exiting fiber **1600**. Condensing lens **1200** converges the light rays on the specimen sample **518**. Objective lens **1202** collects the transmitted light beam and the light scattered from the probe on its back focal plane where it interferometrically forms the Fourier transform of the superposition of these two light fields. Lens **1604** reprojects the optical Fourier transform of the sample from the back focal plane of objective lens **1202** to quadrant photodiode **220**. Quadrant photodiode **220** converts the light into electronic signals indicative of optical intensities at various positions on the surface of quadrant photodiode **220**.

Optical Tracking Theory and Equations

Optical tracking equations based on intensity measurements made by quadrant photodiode **220** are theoretically based on Maxwell's Wave

Equations. The following assumptions were made in order to perform the optical tracking calculations:

1. The probe acts like a Rayleigh scatterer (a dielectric sphere with a radius smaller than the wavelength of the incident light).

2. The finite size of the particle is accounted for, with a dielectric constant, ε, and a polarizability, α,

$$\alpha = a^3 \eta_{solvent}{}^2 \cdot \frac{(m^2-1)}{(m^2+2)}$$

Where

$$m = \frac{\eta_{probe}}{\eta_{solvent}}$$

and η_{probe} and $\eta_{solvent}$ are the refractive indices of the probe and the solvent in which the probe is floating, and *a* is the radius of the probe. To simplify the math, the probe position r' is described in cylindrical coordinates z', $\rho'^2=x'^2+y'^2$, $\varphi'=\text{atan}(y'/x')$, while the detected interference at point **r** is described in spherical coordinates (r, υ, φ) around the optical axis. Figure 17 illustrates the spherical and cylindrical coordinates used in the probe position calculations.

3. The propagating electromagnetic field generated by the laser is modeled as a Gaussian beam with a scalar wavenumber k

$$k = |k| = {}^{2\pi\eta_{solvent}}\!/\!_{\lambda}$$

the radius of curvature of the Gaussian beam is

$$R(z) = z\left[1+\left(\frac{z_0}{z}\right)^2\right]$$

the beam waist radius in the focal plane is

$$\omega_0 = \sqrt{\lambda \frac{z_0}{\pi}}$$

and the phase is

$$\zeta(z) = a\tan\left(\frac{z}{z_0}\right).$$

At the focus (i.e., the sample under test), the field generated by laser **214** undergoes the Gouy-phase jump, resulting in a ninety-degree phase shift between the focused laser field and a simple plane wave description of the phase of the light. The complex amplitude of the incident Gaussian electromagnetic field on the probe is given by

$$E_i(r) = E_0 \frac{w_0}{w(z)} \exp\left[-\frac{\rho^2}{w^2(z)}\right] \exp\left[-ikz - ik\frac{\rho^2}{2R^2(z)} + i\zeta(z)\right] \quad (1)$$

When the field at quadrant photodiode **220** is observed, far from the focal plane ($r >> z_0$), the following approximations can be used:

$$\zeta(z) = \arctan\left(\frac{z}{z_0}\right) \approx \frac{\pi}{2}, z \approx r, R(z) \approx \infty$$

$$\omega(z) \approx \frac{\omega_0 z}{z_0}, \sin(\upsilon) \approx \upsilon, \rho < \omega_0, \exp\left(-\frac{\rho^2}{\omega(z)^2}\right) \approx 1$$

the unscattered light in the far field is then given by

$$E_u(r) = iE_0 \frac{k\omega_0}{2r} \exp\left[ikr - \frac{1}{4}k^2\omega_0{}^2\upsilon^2\right], \quad (2)$$

and this is normalized by

$$E_0 = \frac{2}{\left(\omega_0\sqrt{\pi\varepsilon_S c_S}\right)},$$

where c_S is the speed of light in the sample under test. When a probe with a polarizability α, is placed at a position r', near the geometric focal point, the Rayleigh approximation for the scattered field at large r >> z_0 is

$$E_S(r,r') \approx \frac{k^2\alpha}{r} E(r')\exp[ik|r-r'|] \tag{3}$$

The change in the average light intensity I, due to the interference between the incident laser beam and the scattered light (subtracting the offset $|E|^2$) is

$$\delta I = \frac{\varepsilon_S c_S}{2}\left(|E+E'|^2 - |E|^2\right) \approx \varepsilon_S c_S \operatorname{Re}(EE')$$

Using equations (2) and (3), the intensity change in the back focal plane of objective **1202** for a probe displacement r', from the geometrical focal point of objective **1202** is

$$\frac{\delta I(r,r')}{I_{tot}} = J(r,r')\sin\left[k(r-|r-r'|-z'-\frac{\rho'^2}{2R(z')}+\frac{\zeta(z')}{k}\right] \tag{4}$$

Where

$$J(r,r') = \frac{2k^3\alpha}{\pi r^3}\left(1+\left(z'/z_0\right)^2\right)^{-1/2} \exp\left[-\frac{\rho'^2}{\omega(z')^2} - k^2\omega_0{}^2\vartheta^2\right]$$

The z-signal is extracted from the total intensity at the back focal plane of lens **1202**. Thus, equation (4) can be integrated over all angles to obtain the z-signal along the optical axis as:

$$\frac{I_z}{I}(z') = \frac{8k\alpha}{\pi\omega_0{}^2}\left(1+\left(z'/z_0\right)^2\right)^{-1/2} \sin\left(\arctan\left(\frac{z'}{z_0}\right)\right) \tag{5}$$

Figure 18A is a graph of normalized intensity versus probe displacement in the Z direction (perpendicular to the surface of quadrant photodiode **220**). The graph was generated assuming a 650nm laser, a beam waist radius of 700nm, a probe radius a=300nm, and the refractive indices of the probe and

the sample under test at 1.5 and 1.33, respectively. The result illustrated in Equation 5 and Figure 18A is intuitive--as probe moves towards quadrant photodiode **220** in the Z direction, the normalized intensity increases and as the probe moves away from quadrant photodiode **220**, the normalized intensity decreases. Thus, the change in intensity of the scattered and directly transmitted light measured by quadrant photodiode **220** can be used to track motion of probe **202** in the Z direction.

The lateral probe displacement (i.e., displacement in a plane parallel to the surface of QPD **220**), may be determined by the difference in intensity between two halves of QPD **220**. Thus, it is necessary to integrate half of the detection area to obtain the lateral signals. The two-dimensional result for a probe displacement, p', in the focal plane at an angle φ' is

$$\frac{I_x}{I}(p',\varphi') = \frac{16k\alpha}{\sqrt{\pi\omega_0^{\ 2}}}\cos(\varphi')\left(\frac{\rho'}{\omega_0}\right)\exp\left(-\left(\frac{\rho'}{\omega_0}\right)^2\right) \qquad (6)$$

Figure 18B is a graph of normalized intensity versus displacement in the X direction generated by assuming the same laser, beam waist, beam radius, and probe and sample materials described above with regard to Figure 18A. As illustrated in Figure 18B, normalized intensity is zero for displacements to the far left and the far right of the center of quadrant photodiode **220**. This is because light is being scattered outside of the image plane of quadrant photodiode **220**. In the region near the center of quadrant photodiode **220**, normalized intensity varies approximately sinusoidally with displacement. The results for displacement in the Y direction are similar to those illustrated in Figure 18B for the X direction. Thus, by measuring the intensity and calculating

the change in intensity of light measured by different regions of quadrant photodiode **220**, motion of a mechanically unattached probe can be tracked in a plane parallel to the surface of quadrant photodiode **220**.

Equations (5) and (6) or approximations of Equations (5) and (6) may be implemented as a position calculator in hardware and/or software in computer **204** illustrated in Figure 2. Such a position calculator receives the signals output from quadrant photodiode **220** and calculates position, velocity, and/or acceleration of probe **202** in the sample under test.

Thus, the present invention includes methods and systems for controlling motion of and tracking a mechanically unattached probe. In one implementation, the invention includes a magnetic pole and coil assembly suitable for use in space-constrained environments, such as optical microscopes with high numerical aperture lenses. In order to effect motion of a mechanically unattached probe in three dimensions, upper and lower pole carriers may be patterned with a plurality of pole pieces. Upper and lower magnetic drive ring cores include coils that magnetize the pole pieces to apply magnetic force to the probe. The pole pieces may be manufactured using any suitable manufacturing technique for making thin magnetic materials in predetermined patterns. Examples of fabrication techniques include any semiconductor fabrication techniques or cutting the pole piece patterns from thin foils.

It will be understood that various details of the invention may be changed without departing from the scope of the invention. Furthermore, the foregoing description is for the purpose of illustration only, and not for the

purpose of limitation, as the invention is defined by the claims as set forth hereinafter.